Trait dissection
using a modelling framework
- Examples in maize and wheat -

Karine Chenu et al.

QAAFI, The University of Queensland, Toowoomba
A gene-to-phenotype modelling approach

Gene
Process
Organ
Whole plant
Canopy

QTL (Quantitative Trait Loci)
Leaf Elongation Rate (LER)
Silk Elongation - ASI (Anthesis-Silking Interval)

Yield
A gene-to-phenotype modelling approach

- **Gene**
- **Process**
- **Organ**
- **Whole plant**
- **Canopy**

**QTL** (Quantitative Trait Loci)

- **Leaf Elongation Rate (LER)**
- **Silk Elongation - ASI (Anthesis-Silking Interval)**

Leaf growth for light interception

**Biomass production** vs. **Intercepted Radiation MJ m⁻²**

**Radiation Use Efficiency**
A gene-to-phenotype modelling approach

- Gene
- Process
- Organ
- Whole plant
- Canopy

- QTL (Quantitative Trait Loci)
- Leaf Elongation Rate (LER)
- Silk Elongation - ASI (Anthesis-Silking Interval)
- Yield

silk appearance = female flowering
A gene-to-phenotype modelling approach

Gene
Proc
Org
Whole plant
Canopy

QTL (Quantitative Trait Loci)
Silk Elongation - ASI (Anthesis-Silking Interval)

\[ GY = e^{[2.49 - 1.18 \sqrt{ASI+1}]} \]
\[ r^2 = 0.70; 46 \text{ d.f.} \]

Grain Yield (t/ha)
Anthesis-silking interval (d)

ASI (Time between male and female flowering)
A gene-to-phenotype modelling approach

Evaluate the impact of the QTL on yield in various climatic and drought conditions
Leaf expansion in Maize

Monocot: period of linear expansion

Possibility to follow leaf expansion rate with a 15 minutes definition

Experimental set-up for 360 plants together
Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress

Sadok et al. submitted
Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress

- Under water deficit, the LER time course is accounted by 2 major stress:
  
  . evaporative demand (VPD) only during day time

  \[
  \text{LER} = (T-T_0) (a - b\text{VPD}_{\text{fac}})
  \]

Leaf elongation rate for a 10-d period
Leaf expansion in Maize under drought conditions

- Instantaneous response of leaf expansion to an environmental stress

- Under water deficit, the LER time course is accounted by 2 major stress:

  . evaporative demand (VPD)
    only during day time

    \[ LER = (T-T_0) (a - b VPD) \]

  . leaf predawn potential (ψ)
    Decline of night values

    \[ LER = (T-T_0) (a - c \Psi') \]

Time course modelled by the sum

\[ LER = (T-T_0) (a - b VPD_{fa} - c \Psi') \]
- Instantaneous response of leaf expansion to an environmental stress

- Under water deficit, the LER time course is accounted by 2 major stress:

  . **evaporative demand (VPD)**  
    only during day time
    
    \[
    LER = (T-T_0) (a - bVPD_{fa})
    \]

  . **leaf predawn potential (ψ)**  
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    LER = (T-T_0) (a - c \psi')
    \]

Time course modelled by the sum

\[
LER = (T-T_0) (a - bVPD_{fa} - c \psi')
\]
Leaf expansion in Maize under drought conditions
Response to temperature and soil and air water deficits

LER = \frac{dl}{dt} = (T - T_0)(a + b VPD_{air-leaf} + c \Psi)

1 genotype \rightarrow 1 set of parameters of response curves (parameter ‘indep.’ of env.)

Reymond et al. 2003 Plant Phy
Leaf expansion in Maize under drought conditions

QTL related to env. responses

LER = dl/dt = (T-T_0)(a + b VPD_{air-leaf} + c \Psi)

Welcker et al. 2007

1 genotype → 1 set of parameters of response curves (parameter ‘indep.’ of env.)
Leaf expansion in maize under drought conditions

QTL related to environment responses

QTLs of leaf length were not stable among experiments

Experiment:
- Control 1 (greenhouse)
- Control 2 (field)
- Deficit 1 (greenhouse)
- Deficit 2 (greenhouse)

Reymond et al. 2004 J. Exp Bot
Leaf expansion in maize under drought conditions
QTL related to environment responses

QTLs of leaf length were not stable among experiments
A QTL co-location for slope \( a \) in three populations

Reymond et al. 2004 J. Exp Bot
Modelling the effects of the genetic variability – Example: Leaf expansion rate in maize

\[ \text{LER} = dl/dt = (T-T_0)(a + b \text{VPD}_{\text{air-feuille}} + c \Psi') \]

\[ a = \bar{a} + \sum \alpha \text{QTL} \]
\[ b = \bar{b} + \sum \beta \text{QTL} \]
\[ c = \bar{c} + \sum \gamma \text{QTL} \]

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APSIM (Agricultural Production Systems Simulator)

A modular crop model
Development

- Plant Emergence
  - T, PP

- Leaf Initiation
  - T, W&N
  - LNo

- Anthesis
  - T, W&N
  - A

- Physiol Maturity

Growth

- θ
- kl
- Roots

- Δ Biomass
  - TE
  - vpd
  - A
  - ~A

- Grain Number

- Grain Size & N
  - k
  - SLN
  - N
  - RADN
  - LNo
  - T

- Grain Yield
  - R_{int}

A general cropping system simulation for plant development
Leaf development in APSIM

- Leaf number
- Thermal time
- Total leaf number
- Leaf development
- Leaf growth
- Duration of leaf production
- Keating & Wafula 92
Leaf development in APSIM

Leaf development

- Leaf number
- Total leaf number
- Duration of leaf production
- Leaf initiation rate & duration

Leaf growth

- Thermal time
- Leaf number

Keating & Wafula 92
Leaf development in APSIM

- Leaf number
- Leaf initiation
- Total leaf number
- Duration of leaf production
- Leaf growth
- Total leaf number
- Leaf area profile
- Leaf initiation rate & duration
- Total leaf number
- Final leaf area profile
- Keating & Wafula 92

TLN
## Leaf development in APSIM

<table>
<thead>
<tr>
<th>Leaf development</th>
<th>Leaf growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total leaf number</td>
<td>Duration of leaf production</td>
</tr>
<tr>
<td>Leaf number</td>
<td>thermal time</td>
</tr>
<tr>
<td>Leaf initiation</td>
<td>leaf_no_rate_change</td>
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<tr>
<td>rate &amp; duration</td>
<td>∆1/LIR</td>
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<tr>
<td>Leaf appearance</td>
<td>∆1/LAR1</td>
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<td>(ligulation)</td>
<td>∆1/LAR2</td>
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<td>final leaf area profile</td>
<td>∆ leaf area</td>
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<tr>
<td>potential</td>
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</tbody>
</table>

Keating & Wafula 92

![Graphical representation of leaf development in APSIM](image)
Leaf development in APSIM

Leaf development

- Total leaf number
- Leaf number
- Duration of leaf production
- Thermal time
- Leaf appearance
- Leaf initiation rate & duration
- Total leaf number
- Final leaf area profile
- Water supply / demand
- Potential
- Effective
- Δ leaf area
- Δ leaf area

Leaf growth

Keating & Wafula 92

TLN

24
New APSIM module for leaf development

New APSIM module for leaf development

LER = \left( T_{\text{leaf}} - T_0 \right) \left( a + b \ VPD_{\text{air-leaf}} - c \ \Psi \right)

New APSIM module for leaf development

LER = (T_{leaf} - T_0) (a + b VPD_{air-leaf} - c \Psi)

New APSIM module for leaf development

LER = (T_\text{leaf} - T_0) (a + b \text{VPD}_{\text{air-leaf}} - c \psi)

New APSIM module for leaf development

LER = (T_{leaf} - T_0) (a + b \text{VPD}_{air-leaf} - c \Psi)

Leaf area = \alpha \text{length}_{limb} \times \text{width}_{limb}

Integrating QTL information on leaf growth response into APSIM

Test of the model

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Location</th>
<th>Sowing date</th>
<th>Treatment</th>
<th>Radiation (MJ m(^2))</th>
<th>Rain (mm)</th>
<th>Temperature (°C)</th>
<th>VPD(_{\text{air-meristem}}) (kPa)</th>
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</thead>
<tbody>
<tr>
<td>GR92ap</td>
<td>Grignon, North of France</td>
<td>April 27, 1992</td>
<td>control</td>
<td>21.1</td>
<td>62</td>
<td>15.6</td>
<td>1.098</td>
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<td>GR92ap</td>
<td>Grignon, North of France</td>
<td>April 27, 1992</td>
<td>water deficit</td>
<td>21.1</td>
<td>0</td>
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<td>MP94jl</td>
<td>Montpellier, South of France</td>
<td>July 19, 1994</td>
<td>control</td>
<td>20.7</td>
<td>30</td>
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<td>MP94jl</td>
<td>Montpellier, South of France</td>
<td>July 19, 1994</td>
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<td>1.49</td>
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<td>control</td>
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<td>water deficit</td>
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<td>water deficit</td>
<td>21.6</td>
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<tr>
<td>MA97ma</td>
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<td>MA98ma</td>
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<td>control</td>
<td>23</td>
<td>47</td>
<td>21.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

- 1 situation => Parametrisation of the model
- 11 situations => Test of the model
Test of the model

Accurate predictions of leaf elongation, LAI and yield in contrasting climatic and drought conditions (12 field conditions)

=> Capacity to simulate G x E for leaf area & yield
=> G-to-P prediction

Chenu et al. PCE 2008
Reproductive development

- Common QTLs for ASI and the response of leaf elongation under water deficit

⇒ Effect of the QTLs of ASI integrated in APSIM.

Welcker et al. 2007
Complex interactions between the QTL for a, b, c and ASI
Transpiration Yield …

• Cross-over interactions for yield
• Genetic variability simulated highly varies across env.

Chenu et al. Genetics 2009
Evaluation of the effect on yield in Sete Lagoas - Brazil

Effect of leaf and silk QTL on yield (Brazil)

- Effect of QTL opposite in ET1-2 and ET3-4.
- The mean effects of the QTL on yield
  - ranged from <10 to > 200 kg/ha
  - explained up to 30% of the variance for yield.

- The largest effects occurred when the QTL affecting ASI were included (graphs with different scales).

Very large effect in ET2 in pop2 (specific to the timing of the stress).
Estimation of the yield impact of organ-level QTL

The effect of single QTLs with similar effect on leaf growth may have substantially different effects on yield in different environments.

II - Connecting understanding of traits
- Root architecture and staygreen in wheat -
Connecting understanding of traits
– Example of wheat root system architecture –

Drought adaptation in dryland wheat (G*E)
for contrasting wheat varieties

Yield advantage = 19%

Staygreen phenotype

Connecting understanding of traits
– Example of wheat root system architecture

Controlled experiments => Seri has a root system more compact

Connecting understanding of traits
– Example of wheat root system architecture

Controlled experiments => Seri has - a root system more compact
- a better “occupancy” at depth

Simulated effect of root traits modification on wheat yield

Root archi. with better water extraction at depth

⇒ ↑ yield gain

⇒ 18.7 kg ha\(^{-1}\) for every extra mm of water during the grain filling period

Chenu et al. unpublished
Involvement of roots in staygreen

Better occupancy at depth

Staygreen

Yield Advantage (kg/ha)

Yield

Yield

-20% -10% 0% +10% +20%

-300 -200 -100 0 100 200 300 400 500 600

Grain yield (t ha⁻¹)

2004 2005

-60 -40 -20 0 20 40 60

Extra yield per extra mm of water uptake

-60 -40 -20 0 20 40 60

-20% -10% 0% +10% +20%

Involvement of roots in staygreen
Genetic controls for root architecture

QTL identified using root angle and root number of seedling as a proxy

Better occupancy at depth

Hartog SeriM82

Christopher et al (2013) TAG 126:1563
Involvement of roots in staygreen

Christopher et al (2013) TAG 126:1563
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Root - staygreen
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A. Manschadi (DAFF)